Thermo

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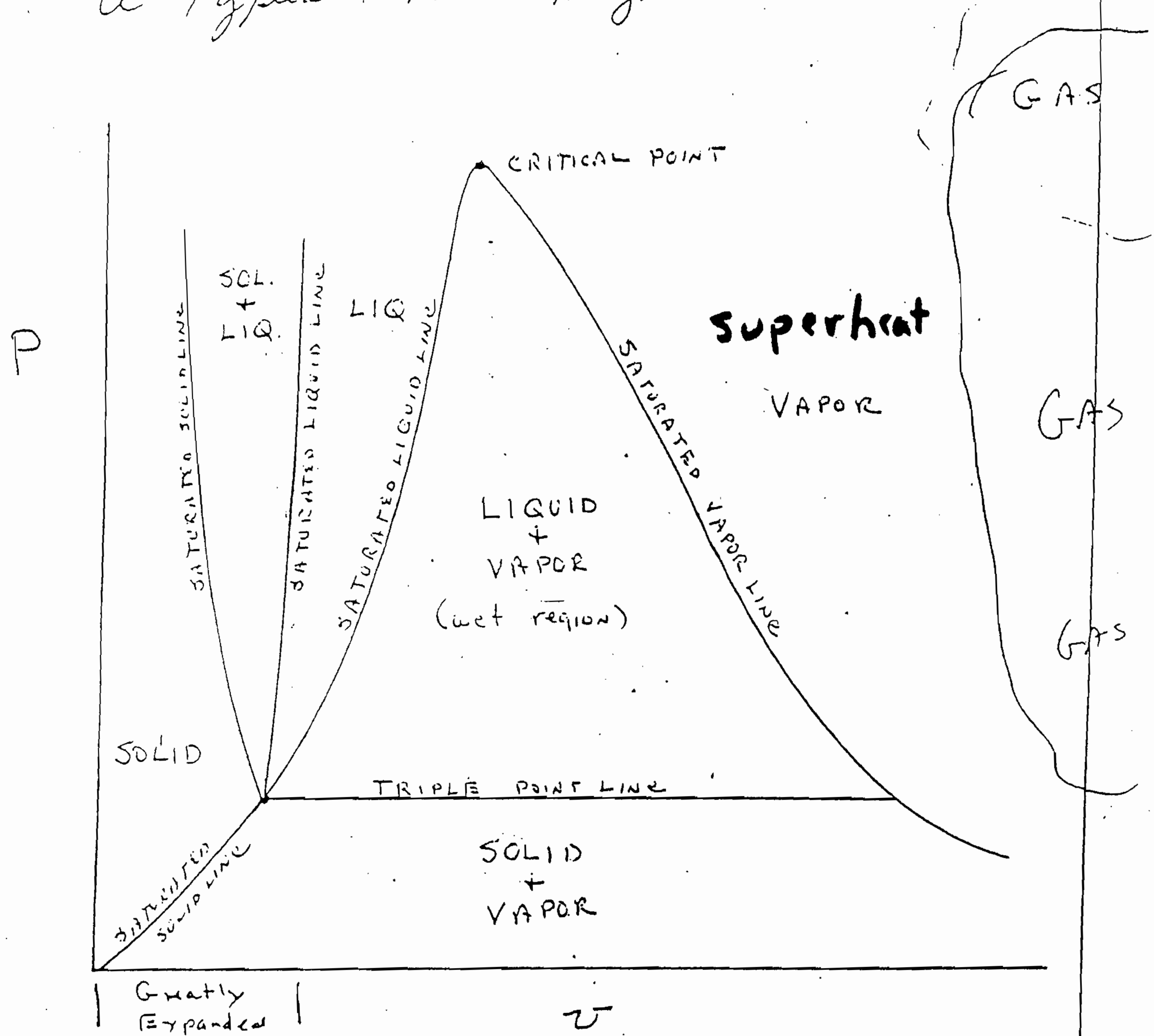
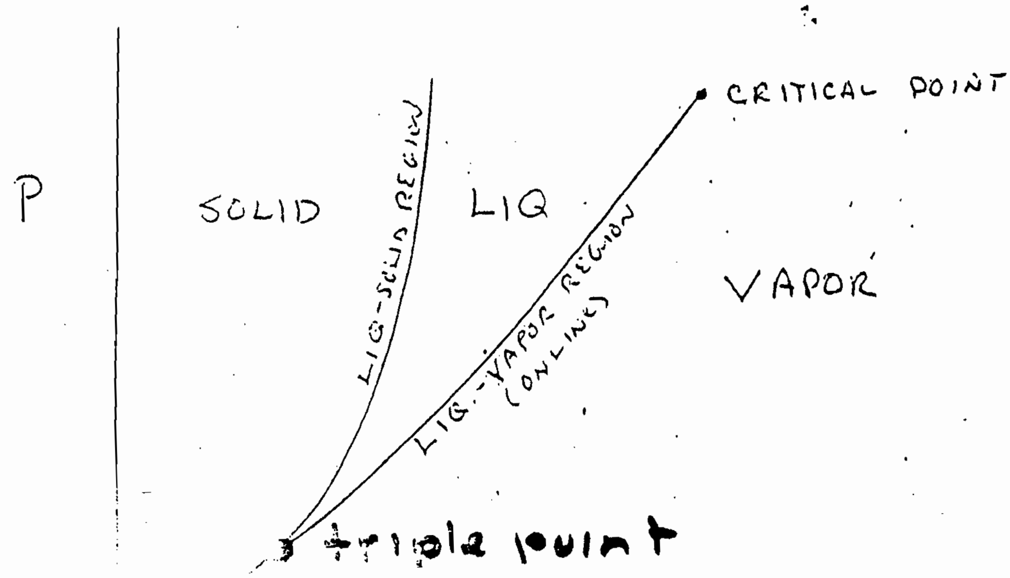
Mechanical PE Review

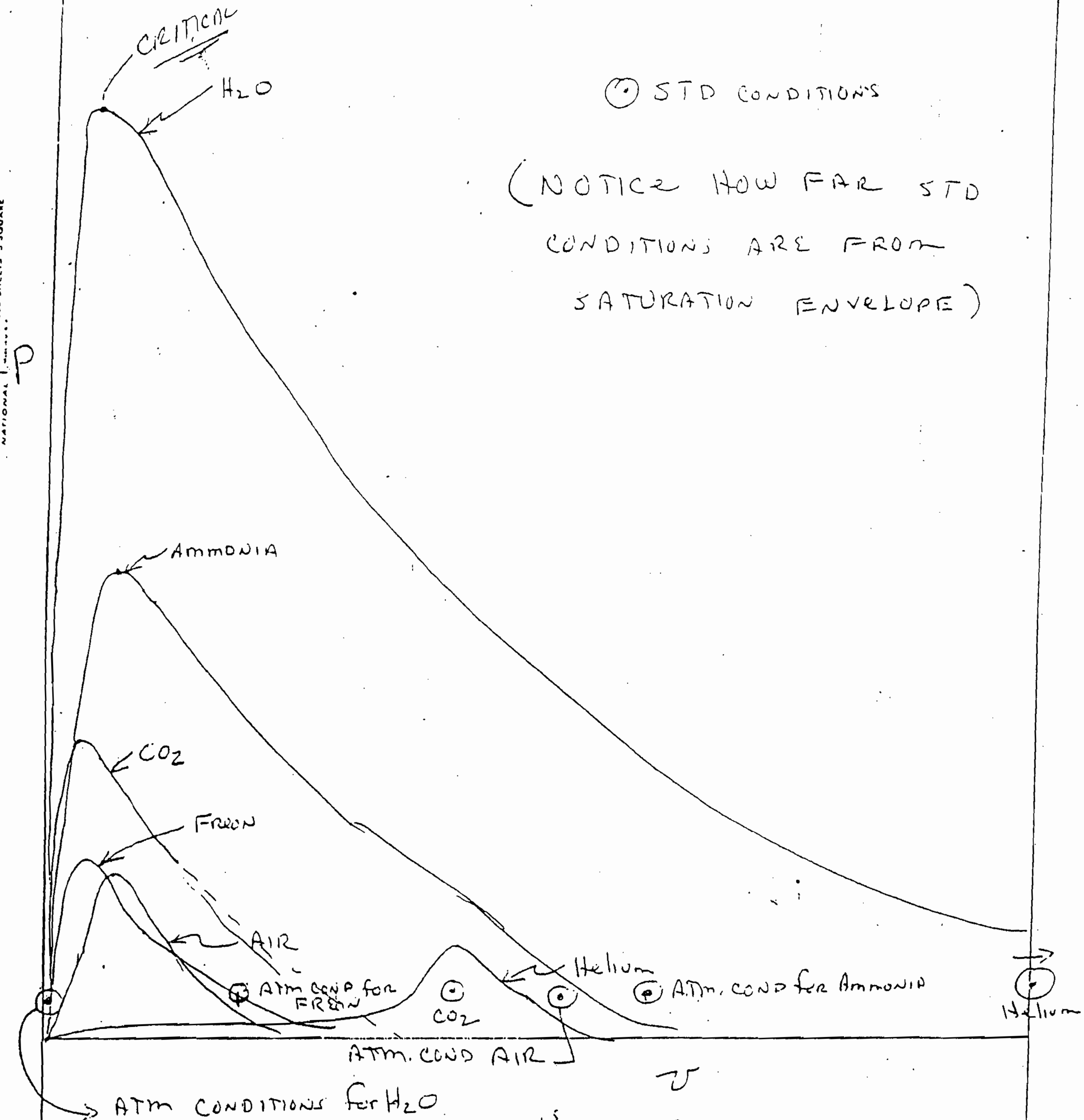
Center for Continuing Engineering Education (C2E2)

A Typical Phase Diagram





Comparison of Saturated Curves for Various Substances



	P_c (psia)	v_c (ft^3/lbm)	T_c (°F)	v_c @ T+P STD
H_2O	3205	.0498	705	.016 lbm/ft³
Ammonia	1635	.0652	270	22 "
CO_2	1073	.0344	88	4.8 lbm/ft³
Freon 12	582	.0293	232	3 lbm/ft³
Air	[illegible]	[illegible]	[illegible]	

THERMODYNAMICS

1st and 2nd Law Formulae for Reversible Processes of an Ideal Gas (per unit mass basis)* (with Constant Specific Heats)

PROCESS	CLOSED SYSTEM (NON-FLOW)	OPEN SYSTEM (STEADY FLOW)	
General ($pv = RT$) $\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$	$q = Cv\ (T_2 - T_1) + w$ $w = \int_1^2 p\,dv$ $s_2 - s_1 = Cp \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \longleftrightarrow$	$q = Cp\ (T_2 - T_1) + \Delta KE + \Delta PE + w$ $w = -\int_1^2 v\,dP - \Delta KE - \Delta PE$ $= Cv \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$	$s_2 - s_1$ is the same for closed or open systems
POLYTROPIC $pv^n = \text{const}$ $\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{n/n-1} = \left(\frac{v_1}{v_2}\right)^{n}$ $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{n-1/n} = \left(\frac{v_1}{v_2}\right)^{n-1}$ $\frac{v_2}{v_1} = \left(\frac{P_1}{P_2}\right)^{1/n} = \left(\frac{T_1}{T_2}\right)^{1/n-1}$	$q = \frac{k-n}{1-n}\ Cv(T_2 - T_1)$ $w = \frac{k-1}{1-n}\ Cv(T_2 - T_1)$ $s_2 - s_1 = Cp \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \longleftrightarrow$	$q = \frac{k-n}{1-n}\ Cv(T_2 - T_1)$ $w = n\ \frac{k-1}{1-n}\ Cv(T_2 - T_1) - \Delta KE - \Delta PE$ $= Cv \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$	$s_2 - s_1$ is the same for closed or open systems
Constant Volume (Isometric) $v_2 = v_1 \quad n = \infty$ $\frac{P_2}{T_2} = \frac{P_1}{T_1}$	$q = Cv\ (T_2 - T_1)$ $w = 0$ $s_2 - s_1 = Cv \ln (T_2/T_1)$	$q = Cv\ (T_2 - T_1)$ $w = -v(P_2 - P_1) - \Delta KE - \Delta PE$ $s_2 - s_1 = Cv \ln (T_2/T_1)$	

PROCESS	CLOSED SYSTEM	OPEN SYSTEM
Constant Pressure (Isobaric) $P_2 = P_1 \quad n = 0$ $\frac{v_2}{T_2} = \frac{v_1}{T_1}$	$q = Cp\ (T_2-T_1)$ $w = p\ (v_2-v_1)$ $w = R\ (T_2-T_1)$ $s_2-s_1 = Cp\ \ln\ (T_2/T_1)$	$q = Cp\ (T_2-T_1)$ $w = -\Delta KE - \Delta PE$ $s_2-s_1 = Cp\ \ln\ (T_2/T_1)$
Const. Temperature (Isothermal) $T_2 = T_1 \quad n = 1$ $P_2 v_2 = P_1 v_1$	$q = w = T(s_2-s_1)$ $q = w = RT\ \ln\ \frac{v_2}{v_1}$ or $\frac{P_1}{P_2}$ $s_2-s_1 = R\ \ln\ \frac{v_2}{v_1}$ or $\frac{P_1}{P_2}$	$q = T(s_2-s_1) = RT\ \ln\ \frac{v_2}{v_1}$ or $\frac{P_1}{P_2}$ $w = RT\ \ln\ \frac{v_2}{v_1}$ or $\frac{P_1}{P_2}$ $-\Delta KE - \Delta PE$ $s_2-s_1 = R\ \ln\ \frac{v_2}{v_1}$ or $\frac{P_1}{P_2}$
ADIABATIC (Isentropic) $n = k$ $s_2 = s_1$	$q = 0$ $w = Cv\ (T_1-T_2)$ $w = \frac{P_1 v_1 - P_2 v_2}{k-1}$ $w = R(T_1-T_2)/k-1$ $s_2-s_1 = 0$	$q = 0$ $w = cp\ (T_1-T_2) - \Delta KE - \Delta PE$ $w = \frac{k(P_1 v_1 - P_2 v_2)}{k-1} - \Delta KE - \Delta PE$ $w = KR(T_1-T_2)/k-1 - \Delta KE - \Delta PE$ $s_2-s_1 = 0$

*Constant (Average) Specific Heats (Cv, Vp) assumed. $R = Cp-Cv$, $k = Cp/Cv$, $Cp = kR/(k-1)$, $Cv = R/(k-1)$

$\Delta u = u_2-u_1 = Cv\ (T_2-T_1)$, $\quad \Delta h = h_2-h_1 = Cp\ (T_2-T_1)$

$\Delta KE = \frac{\vec{V}_2^{\,2} - \vec{V}_1^{\,2}}{2g_c \times 1000}$ $\quad \Delta PE = \frac{g(z_2-z_1)}{g_c \times 1000}$ $\quad$ NOTE: ΔKE and ΔPE may be negligible for many open systems

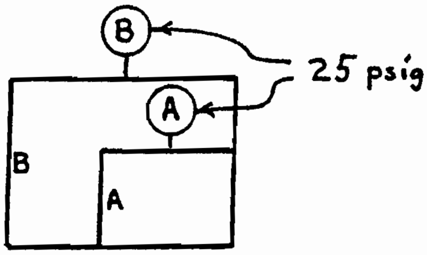
Problem *2.1

Referring to Figure 2.10 in the text, the atmospheric pressure is 100 kPa and the pressure gages A and B read 25 psig. Determine the absolute pressures in boxes A and B in (a) psia; (b) in. Hg absolute.

Given: Atmospheric pressure and readings of gages A and B.

Find: The absolute pressures in boxes A and B.

Sketches and Given Data:



$P_{surr} = 100$ kPa

Assumptions: None

Analysis: Convert atmospheric pressure to psia.

$$(100\text{ kPa})\left(\frac{1\text{ psi}}{6.8948\text{ kPa}}\right) = 14.5\text{ psia}$$

Determine pressures A and B in psia, then convert to in Hg absolute.

a) $$P_{B_{abs}} = P_{B_{gage}} + P_{surr}$$

$$= 25\text{ psia} + 14.5\text{ psia} = 39.5\text{ psia}$$

$$P_{A_{abs}} = P_{A_{gage}} + P_{surr_A} \text{ but } P_{surr_A} = P_{B_{abs}}$$

$$= 25\text{ psia} + 39.5\text{ psia} = 64.5\text{ psia}$$

b) $$P_{B_{abs}} = (39.5\text{ psia})\left(\frac{1\text{ inHg}}{0.4912\text{ psia}}\right) = 80.42\text{ in Hg absolute}$$

$$P_{A_{abs}} = (64.5\text{ psia})\left(\frac{1\text{ inHg}}{0.4912\text{ psia}}\right) = 131.3\text{ in Hg absolute}$$

Problem *2.6

Determine the pressure at points A and B if the density of mercury is 724.4 lbm/ft^3 and that of water is 62.4 lbm/ft^3. Refer to sketch for problem 2.16 (SI).

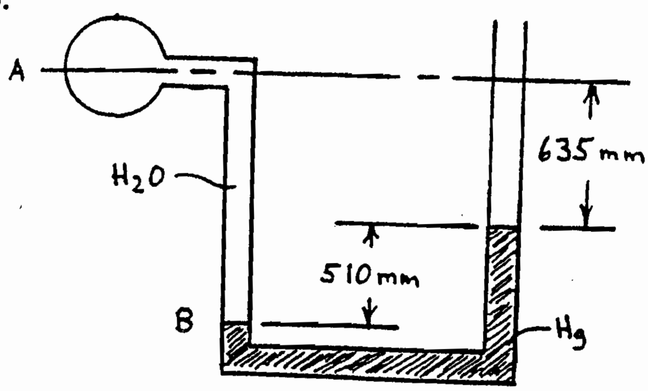
Given: Fluid densities and heights.

Find: Pressures at points A and B.

Sketch and Given Data:

$\rho_{H_2O} = 62.4\ \text{lb}_m/\text{ft}^3$

$\rho_{Hg} = 724.4\ \text{lb}_m/\text{ft}^3$



Assumptions:
1) Atmospheric pressure is 14.696 psia
2) Acceleration of gravity is 32.1739 ft/sec^2.

Analysis: Converting heights to feet.

$$(635\ \text{mm})\left(\frac{1\ \text{in}}{25.4\ \text{mm}}\right)\left(\frac{1\ \text{ft}}{12\ \text{in}}\right) = 2.083\ \text{ft}$$

$$(510\ \text{mm})\left(\frac{1\ \text{in}}{25.4\ \text{mm}}\right)\left(\frac{1\ \text{ft}}{12\ \text{in}}\right) = 1.673\ \text{ft.}$$

Pressure at B is atmospheric plus 1.673 ft column of mercury.

$$P_B = P_{surr} + \frac{\rho L g}{g_c} = 14.696\ \text{psia} + \frac{(724.4\ \text{lbm/ft}^3)(1.673\ \text{ft})(32.1739\ \text{ft/sec}^2)}{(144\ \text{in}^2/\text{ft}^2)(32.1739\ \text{lbm-ft/lb}_f\text{-sec}^2)}$$

$$= 23.1\ \text{psia}$$

Pressure at A is pressure at B minus 3.756 ft column of water.

$$P_A = P_B - \frac{\rho L g}{g_c} = 23.1\ \text{psia} - \frac{(62.4\ \text{lbm/ft}^3)(3.756\ \text{ft})(32.1739\ \text{ft/sec}^2)}{(144\ \text{in}^2/\text{ft}^2)(32.1739\ \text{lbm-ft/lb}_f\text{-sec}^2)}$$

$$= 21.5\ \text{psia}$$

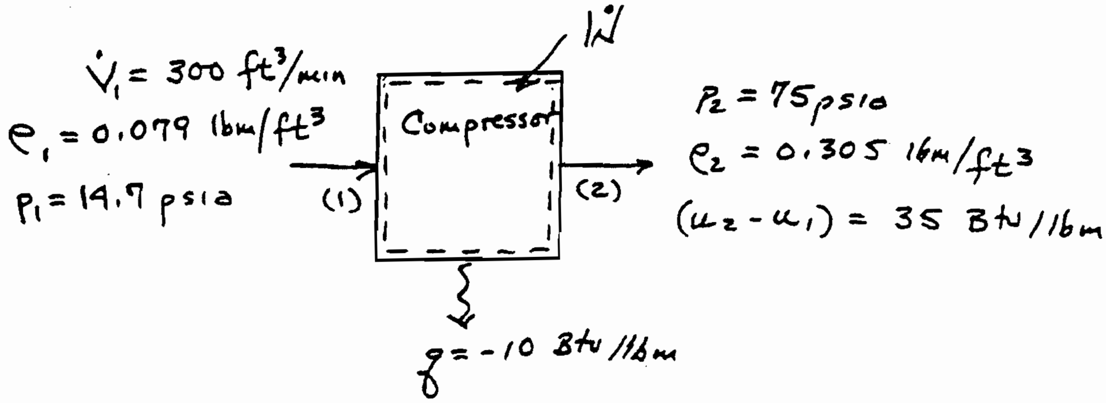
Problem *3.5

An air compressor handles 300 ft³/min of air with a density of 0.079 lbm/ft³ and a pressure of 14.7 psia, and it discharges at a pressure of 75 psia with a density of 0.305 lbm/ft³. The change in specific internal energy across the compressor is 35 Btu/lbm, and the heat loss by cooling is 10 Btu/lbm. Neglecting changes in kinetic and potential energies, find the power in Btu per hour, horsepower, and kilowatts.

Given: A compressor receives a steady flow of air through it. The inlet and discharge are given.

Find: The power required.

Sketch & Given Data:



Assumptions:

1) The compressor is a steady-state open system.

2) Neglect kinetic and potential energies.

Analysis: The first law for a steady-state open system is:

$$\dot{Q} + \dot{m}(u+p/\rho+ke+pe)_1 = \dot{W} + \dot{m}(u+p/\rho+ke+pe)_2$$

Apply assumption (2):

$$\dot{Q} + \dot{m}(u+p/\rho)_1 = \dot{W} + \dot{m}(u+p/\rho)_2$$

$$\dot{Q} + \dot{m}p_1/\rho_1 = \dot{W} + \dot{m}[(u_2-u_1)+p_2/\rho_2]$$

The mass flowrate is not given, so it must be found from volume flowrate.

$$\dot{m} = \rho_1 \dot{V}_1 = \left(0.079\frac{\text{lbm}}{\text{ft}^3}\right)\left(300\frac{\text{ft}^3}{\text{min}}\right) = 23.7\frac{\text{lbm}}{\text{min}}$$

The heat flux, is $\dot{Q} = \dot{m}q$. Substitute data in the first law equation.

$$\left(-10\frac{\text{Btu}}{\text{lbm}}\right)\left(23.7\frac{\text{lbm}}{\text{min}}\right) + \left(23.7\frac{\text{lbm}}{\text{min}}\right)\left(14.7\frac{\text{lb}_f}{\text{in}^2}\right)\left(144\frac{\text{in}^2}{\text{ft}^2}\right)\left(\frac{1}{0.079}\frac{\text{ft}^3}{\text{lbm}}\right)\left(\frac{1\ \text{Btu}}{778.16\ \text{ft-lb}_f}\right) =$$

$$\dot{W} + \left(23.7\frac{\text{lbm}}{\text{min}}\right)\left[\left(89.7\frac{\text{lb}_f}{\text{in}^2}\right)\left(144\frac{\text{in}^2}{\text{ft}^2}\right)\left(\frac{1\text{ft}^3}{0.305\ \text{lbm}}\right)\left(\frac{1\text{Btu}}{778.16\ \text{ft-lb}_f}\right) + (35\ \text{Btu/lbm})\right]$$

$$\dot{W} = -1540\frac{\text{Btu}}{\text{min}} = -92{,}415\frac{\text{Btu}}{\text{hr}} = -36.3\ \text{hp} = -27.1\ \text{kW}$$

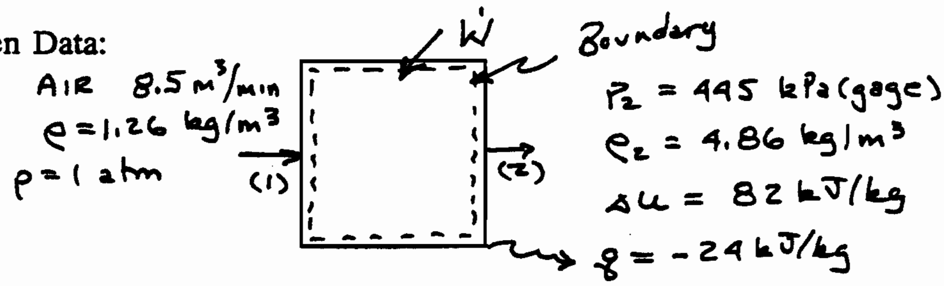
Problem 3.12

An air compressor handles 8.5 m^3/min of air with a density of 1.26 kg/m^3 and a pressure of 1 atm, and it discharges at 445 kPa (gage) with a density of 4.86 kg/m^3. The change in specific internal energy across the compressor is 82 kJ/kg and the heat loss by cooling is 24 kJ/kg. Neglecting changes in kinetic and potential energies, find the power in kilowatts.

Given: The volume flowrate of air entering a compressor at specified conditions, the heat loss from the compressor and the specified air conditions leaving the compressor.

Find: The power required for the compressor.

Sketch & Given Data:



Assumptions:

1) The air compressor is a steady-state open system.

2) Neglect changes in kinetic and potential energies.

Analysis: The first law for an open, steady-state system is:

$$\dot{Q} + \dot{m}\,[u + p/\rho + ke + pe]_1 = \dot{W} + \dot{m}\,[u + p/\rho + ke + pe]_2$$

The mass flowrate of air can be determined from:

$$\dot{m} = \rho_1 \dot{V}_1 = (1.26\ \text{kg/m}^3)\left(8.5\frac{\text{m}^3}{\text{min}}\right)\left(\frac{1\ \text{min}}{60\ \text{sec}}\right)$$

$$\dot{m} = 0.1785\ \text{kg/s}$$

Apply assumption (2) to the first law and substitute into the resulting equation.

$$(-24k\ \mathrm{J/kg})(0.1785\ \mathrm{kg/s}) + (0.1785\ \mathrm{kg/s})\left[(u_1\ \mathrm{kJ/kg}) + (101.3\frac{\mathrm{kN}}{\mathrm{m^2}})(\frac{1}{1.26}\frac{\mathrm{m^3}}{\mathrm{kg}})\right]$$

$$= \dot{W}(\mathrm{kW}) + (0.1785\mathrm{kg/s})\left[\left(u_2\frac{\mathrm{kJ}}{\mathrm{kg}}\right) + \left(546.3\frac{\mathrm{kN}}{\mathrm{m^2}}\right)\left(\frac{1}{4.86}\frac{\mathrm{m^3}}{\mathrm{kg}}\right)\right]$$

$$u_2 - u_1 = 82\ \mathrm{kJ/kg}$$

The power is

$$\dot{W} = \underline{-24.6\ \mathrm{kW}}$$

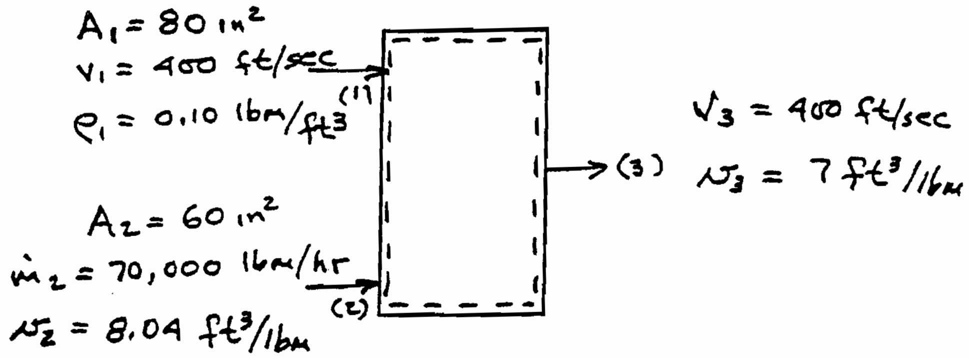
Problem *3.6

Two gaseous streams containing the same fluid enter a mixing chamber and leave as a single stream. For the first gas the entrance conditions are $A_1 = 80$ in.^{2}, $v_1 = 400$ ft/sec, $\rho_1 = 0.10$ lbm/ft^3. For the second gas the entrance conditions are $A_2 = 60$ in.^{2}, $\dot{m}_2 = 70{,}000$ lbm/hr, $\nu_2 = 8.04$ ft^3/lbm. The exit stream condition is $v_3 = 400$ ft/sec, and $\nu_3 = 7$ ft^3/lbm. Determine (a) the total mass flow leaving the chamber; (b) velocity of gas 2.

Given: A mixing chamber receives two fluid streams and discharges a single fluid stream.

Find: The mass flowrate leaving the mixing chamber and the velocity of the second inlet fluid.

Sketch & Given Data:



Assumptions: 1) The mixing chamber is a steady-state open system.

Analysis: The information given and the questions asked in this problem are related to mass flowrate. Hence, starting with the conservation of mass for steady flow conditions is a wise place to begin.

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$$
$$\dot{m} = \rho A v$$

In this case $\dot{m}_1$ is not known, so solve for it.

$$\dot{m}_1 = \left(0.10\frac{\text{lbm}}{\text{ft}^3}\right)\left(\frac{80\text{in}^2}{144\text{in}^2/\text{ft}^2}\right)\left(400\frac{\text{ft}}{\text{sec}}\right) = 22.22\frac{\text{lbm}}{\text{sec}}$$

$$\dot{m}_1 = 80{,}000\frac{\text{lbm}}{\text{hr}}$$

a) $\dot{m}_3 = 80{,}000 + 70{,}000 = \underline{150{,}000 \text{ lbm/hr}}$

The velocity of gas 2 is found from the conservation of mass equation.

$$\dot{m}_2 = \rho_2 A_2 v_2$$

$$\left(19.44\frac{\text{lbm}}{\text{sec}}\right) = \left(\frac{1 \text{ lbm}}{8.04\text{ft}^3}\right)\left(\frac{60\text{in}^2}{144\text{in}^2/\text{ft}^2}\right)(v_2 \text{ ft/sec})$$

b) $v_2 = \underline{375.2 \text{ ft/sec}}$

Problem *3.7

Steam with a flow rate of 3000 lbm/hr enters an adiabatic nozzle at 200 psia, 600 ft/min, with a specific volume of 2.36 ft³/lbm, and with a specific internal energy of 1122.7 Btu/lbm. The exit conditions are p = 20 psia, specific volume = 17.6 ft³/lbm, and internal energy = 973 Btu/lbm. Determine the exit velocity.

Given: A nozzle receives a steady flow of steam, increasing its velocity. The steam states into and from the nozzle are known.

Find: The steam's exit velocity.

Sketch & Given Data:

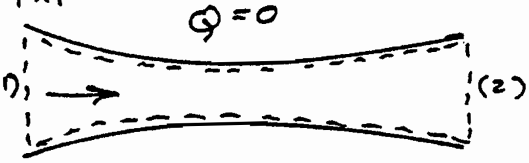
$\dot{m} = 3000$ lbm/hr

$p_1 = 200$ psia

$V_1 = 600$ ft/min

$v_1 = 2.6$ ft³/lbm

$u_1 = 1122.7$ Btu/lbm



$p_2 = 20$ psia

$v_2 = 17.6$ ft³/lbm

$u_2 = 973$ Btu/lbm

Assumptions:

1) The nozzle is a steady-state open system.

2) Neglect changes in potential energy.

3) The heat and work transfer are zero.

Analysis: The first law for a steady-open system is

$$\dot{Q} + \dot{m}(u+pv+ke+pe)_1 = \dot{W} + \dot{m}(u+pv+ke+pe)_2$$

Apply assumptions 2 and 3 and divide by the mass flowrate, yielding

$$u_1 + p_1v_1 + ke_1 = u_2 + p_2v_2 + ke_2$$

Substitute the data into the equation

$$\left(1122.7\frac{\text{Btu}}{\text{lbm}}\right) + \left(200\frac{\text{lb}_f}{\text{in}^2}\right)\left(144\frac{\text{in}^2}{\text{ft}^2}\right)\left(2.36\frac{\text{ft}^3}{\text{lbm}}\right)\left(\frac{1}{778.16(\text{ft-lb}_f)/\text{Btu}}\right)$$

$$+ \frac{(10\text{ft/sec})^2}{(2)\left(32.174\frac{\text{lbm-ft}}{\text{lf}_f\text{-sec}^2}\right)\left(778.16\frac{\text{ft-lb}_f}{\text{Btu}}\right)}$$

$$= (973\ \text{Btu/lbm}) + \frac{\left(20\frac{\text{lb}_f}{\text{in}^2}\right)(144\text{in}^2/\text{ft}^2)(17.6\text{ft}^3/\text{lbm})}{(778.16\ \text{ft-lb}_f/\text{Btu})} + ke_2$$

$$ke_2 = 171.9\frac{\text{Btu}}{\text{lbm}}$$

$$\frac{1}{2}\frac{(v_2\ \text{ft/sec})^2}{\left(32.174\frac{\text{lbm-ft}}{\text{lb}_f\text{-sec}^2}\right)(778.16\ \text{ft-lb}_f/\text{Btu})} = 171.9\frac{\text{Btu}}{\text{lbm}}$$

$$v_2 = \underline{2934\ \text{ft/sec}}$$

Problem *3.22

A 1500 W electric hair dryer is essentially an adiabatic duct and consists of a small fan which blows air over a heating element, increasing the temperature of the air from its inlet temperature of 77 F to an exit temperature of 127 F. The air density at inlet conditions is 0.0739 lbm/ft³ and at outlet conditions is 0.0709 lbm/ft³. The specific internal energy changes from 91.5 Btu/lbm at inlet to 100.1 Btu/lbm at outlet. The pressure remains constant at 14.7 psia throughout the hair dryer. The exit cross-sectional area of the hair dryer when the nozzle is in place is 1 in². Determine:

a) The mass flowrate of air through the dryer;

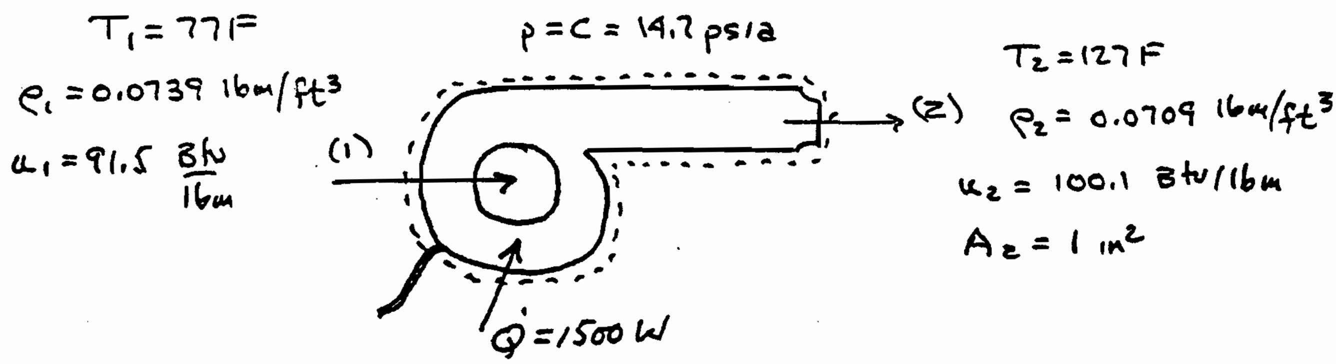
b) The volume flowrate of air at inlet conditions;

c) The velocity of the air leaving the nozzle.

Given: An electric hair dryer with inlet and outlet air conditions as well as exit nozzle area.

Find: The air mass and volume flowrates and the exit air velocity.

Sketch & Given Data:



Assumptions:

1) Steady state, steady flow.

2) Neglect potential energy.

3) The power of fan is negligible compared to heating element.

4) When the nozzle is not in place, the inlet and exit velocities are essentially the same, hence the change of kinetic energy is zero.

Analysis: a) The first law for an open system for part (a) is

$$\dot{Q} + \dot{m}(u+p/\rho+ke+pe)_1 = \dot{W} + \dot{m}(u+p/\rho+ke+pe)_2$$

Applying assumptions (2), (3), (4) yields:

$$\dot{Q} = \dot{m}[(u_2-u_1)+(p_2/\rho_2-p_1/\rho_1)]$$

$$(1.5kW)\left(56.87\frac{Btu}{min-kW}\right) = (\dot{m}\ lbm/min)[(100.1-91.5\ Btu/lbm) +$$

$$\frac{(14.7lb_f/in^2)(144in^2/ft^2)}{\left(778.16\frac{ft-lb_f}{Btu}\right)}\left[\left(\frac{1}{0.0709\ lbm/ft^3}\right)-\left(\frac{1}{0.0739\ lbm/ft^3}\right)\right]$$

$$85.305 = (\dot{m})[8.6 + 1.55]$$

$$\dot{m} = \underline{8.4\ lbm/min}$$

b) The volume flowrate at inlet conditions is

$$\dot{V}_i = \dot{m}v_i = \dot{m}(1/\rho_i) = (8.4\ lbm/min)\left(\frac{1}{(0.0739lbm/ft^3)}\right)$$

$$\dot{V}_i = \underline{113.7\ ft^3/min}$$

c) The velocity leaving the in^2 nozzle is found from the conservation of mass.

$$\dot{m} = \rho_2 A_2 v_2$$

$$(8.4\ lbm/min) = \left(0.0709\frac{lbm}{ft^3}\right)(1\ in^2)\left(\frac{1}{144\ in^2/ft^2}\right)(v_2\ ft/min)$$

$$V_2 = 17060\ ft/min = 284.3\ ft/sec$$

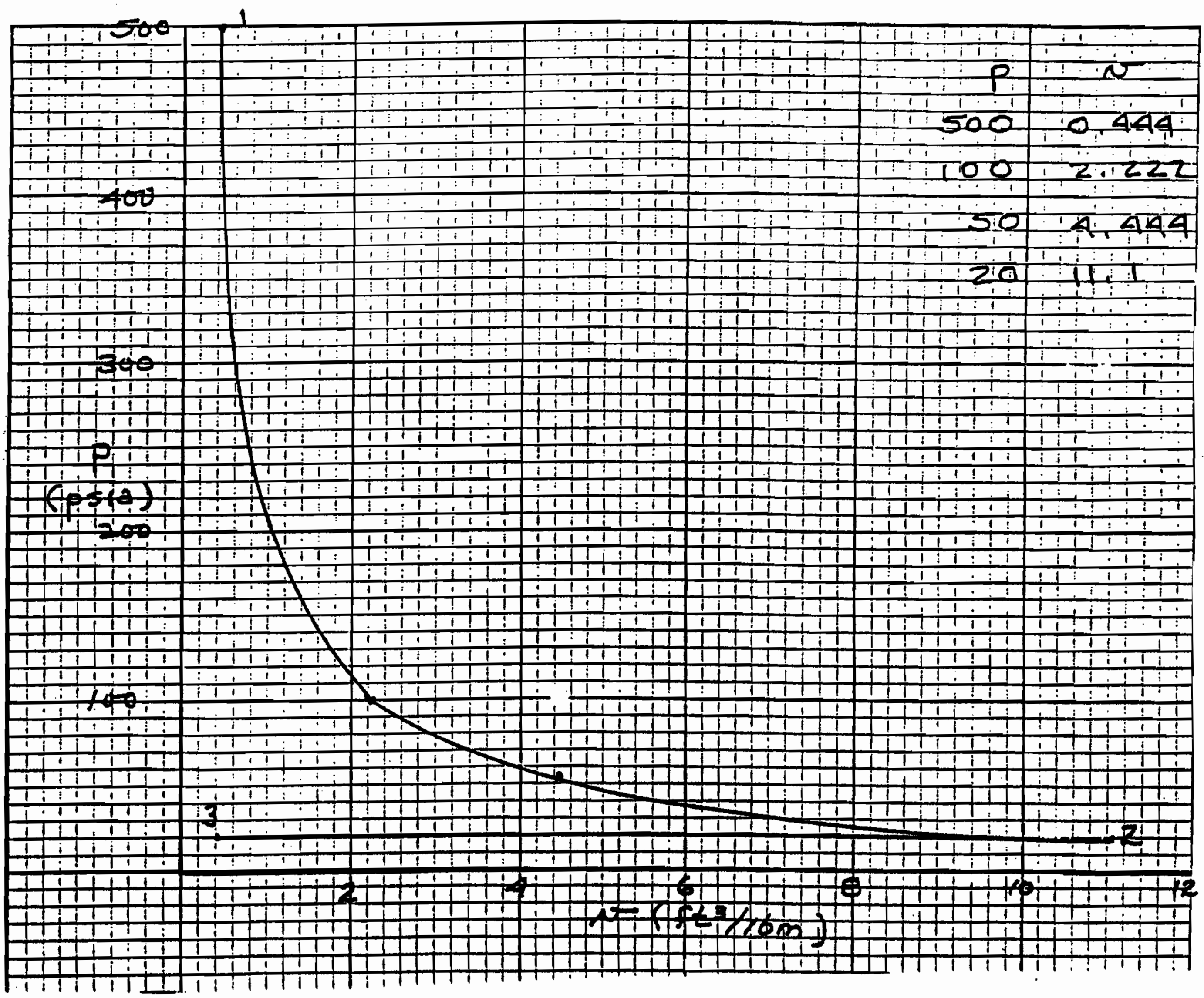
Problem *3.27

Air contained in a piston cylinder undergoes two processes in series. In the first the air expands according to $pv = C$ from 500 psia and a specific volume of 0.444 ft^3/lbm to a pressure of 20 psia. The second process is a constant pressure compression until specific volume three equals specific volume one. Sketch the precesses on a pv diagram and determine the work per unit mass.

Given: Air in a piston cylinder undergoes two defined processes, one after the other.

Find: Sketch the processes on a pv diagram and determine the work in Btu/lbm.

Sketch & Given Data:



Assumptions:
1) The air in the piston/cylinder is a closed system.
2) Neglect kinetic and potential energies.
3) The processes are quasi-equilibrium ones.

Analysis: Find the work for each process and add them together. The work for process 1-2 is

$$W_{1\text{-}2} = \int p\,dv = \int c\frac{dv}{v} = c\ \ln\left(\frac{v_2}{v_1}\right) = p_1 v_1 \ln\left(\frac{v_2}{v_1}\right)$$

$$p_2 v_2 = p_1 v_1 \quad \text{hence} \quad v_2/v_1 = p_1/p_2 \qquad v_2 = 25 v_1$$

$$W_{1\text{-}2} = p_1 v_1 \ln\left(\frac{p_1}{p_2}\right) = \frac{\left(500\frac{\text{lb}_f}{\text{in}^2}\right)\left(144\frac{\text{in}^2}{\text{ft}^2}\right)\left(0.444\frac{\text{ft}^3}{\text{lbm}}\right)\ln\left(\frac{500}{20}\right)}{(778.16\ \text{ft-lb}_f/\text{Btu})}$$

$$W_{1\text{-}2} = 132.2\ \text{Btu/lbm}$$

For the process 2-3 the work is

$$W_{2\text{-}3} = \int p\,dv = p(v_3 - v_2) = \frac{\left(20\frac{\text{lb}_f}{\text{in}^2}\right)\left(144\frac{\text{in}^2}{\text{ft}^2}\right)(0.444 - 11.1\ \text{ft}^3/\text{lbm})}{(778.16\ \text{ft-lb}_f/\text{Btu})}$$

$$W_{2\text{-}3} = -39.4\frac{\text{Btu}}{\text{lbm}}$$

$$W_{3\text{-}1} = 0 \quad \text{for} \quad v = c$$

The net work is

$$W_{net} = 132.2 - 39.4 = 92.8\ \text{Btu/lbm}$$

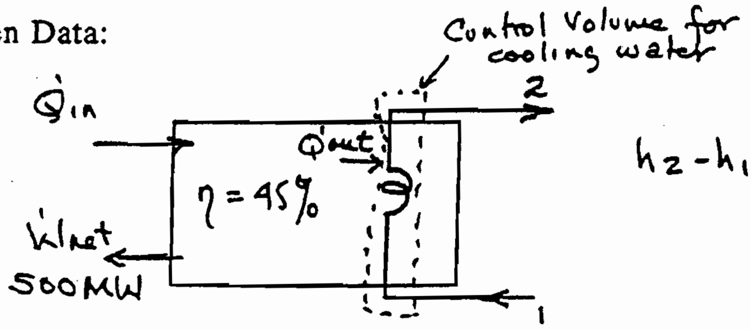
Problem *3.41

A power plant produces 500 MW of electric power while operating with an efficiency of 45%. The heat rejected from the cycle goes into cooling water supplied from an adjacent river. The water's enthalpy increases by 20 Btu/lbm as it receives the heat rejected. Determine the mass flowrate of water required.

Given: A power plant produces a given amount of power at a known efficiency. In doing so the heat flow from the plant enters a river.

Find: The flowrate of water required for cooling.

Sketch & Given Data:



$h_2 - h_1 = 20$ Btu/lbm

Assumptions:

1) The cycle is a closed system.

2) Neglect changes in kinetic and potential energy of the cooling water and there is no work done in the cooling process.

Analysis: For a power producing cycle,

$$\eta_{Th} = \frac{\dot{W}net}{\dot{Q}in}$$

$$0.45 = \frac{500}{\dot{Q}in}$$

$$\dot{Q}in = 1111.1 \text{ MW}$$

For any cycle:

$$\dot{W}net = \dot{Q}in + \dot{Q}out$$

$$500 = 1111.1 + \dot{Q}out$$

$$\dot{Q}out = -611.1MW$$

$$\dot{Q}out = (-611.1MW)\left(1000\frac{kW}{MW}\right)\left(3412.2\frac{Btu}{hr\text{-}kW}\right) = 2.0852 \times 10^{9}\frac{Btu}{hr}$$

From a first law analysis on the cooling water (where the heat is entering the cooling water; hence positive from the water's view).

$$\dot{Q} + \dot{m}(h+ke+pe)_1 = \dot{W} + \dot{m}(h+ke+pe)_2$$

Apply assumption (2)

$$\dot{Q} + \dot{m}h_1 = \dot{m}h_2$$

$$\left(2.0852 \times 10^{9}\frac{Btu}{hr}\right) = \left(\dot{m}\frac{lbm}{hr}\right)\left(20\frac{Btu}{lbm}\right)$$

$$\dot{m} = \underline{1.042 \times 10^{8}\frac{lbm}{hr}}$$

Problem *4.1

Fill in the data omitted in the following table for water.

	Pressure (psia)	Temperature (°F)	Specific volume (ft^3/lbm)	Enthalpy (Btu/lbm)	Quality x(%)	State
(a)	500		0.650			
(b)		250		1000		
(c)	600	700				
(d)	800			1399.1		
(e)		300			90	
(f)	1000	200				

Indicate for each state whether the state is subcooled liquid, saturated liquid, mixture, saturated vapor or superheated vapor.

Given: Two independent steam properties.

Find: Remaining properties and state of steam.

Assumption: 1) The water is in equilibrium.

Analysis: (a) Using Appendix A.15 at 500 psia, specific volume is between v_f and v_g, therefore this is a mixture. From Appendix A.15.

$T = 467.02°F$ $\qquad$ $h_f = 449.67$ Btu/lbm

$v_f = 0.019739$ ft^3/lbm $\qquad$ $h_{fg} = 755.64$ Btu/lbm

$v_g = 0.92849$ ft^3/lbm

$$v = v_f + x(v_g - v_f)$$

$$0.65 \text{ ft}^3/\text{lbm} = 0.019739 \text{ ft}^3/\text{lbm} + x(0.92849 \text{ ft}^3/\text{lbm} - 0.019739 \text{ ft}^3/\text{lbm})$$

$$x = 0.694$$

$$h = h_f + x\,h_{fg} = 449.67 \text{ Btu/lbm} + (0.694)(755.64 \text{ Btu/lbm})$$

$$= 974.1 \text{ Btu/lbm}$$

(b) Using Appendix A.14 at 250°F, enthalpy is between h_f and h_g, therefore, this is a mixture. From Appendix A.15.

$P = 29.864$ psia $\quad h_f = 218.66$ Btu/lbm

$v_f = 0.017005$ ft^3/lbm $\quad h_{fg} = 945.59$ Btu/lbm

$v_g = 13.808$ ft^3/lbm

$h = h_f + x\, h_{fg}$

1000 Btu/lb = 218.66 Btu/lbm + (x)(945.59 Btu/lbm)

$x = 0.826$

$v = v_f + x(v_g - v_f) = 0.017005$ ft^3/lbm

+ (0.826)(13.808 ft^3/lbm - 0.017005 ft^3/lbm)

= 11.41 ft^3/lbm

(c) From appendix A.16, since temperature is above saturation for 600 psia, this is a superheated vapor.

$v = 1.0732$ m^3/kg $\quad h = 1351.4$ Btu/lbm

(d) From appendix A.16, since enthalpy is above h_g for 800 psia, this is a superheated vapor.

$T = 800$°F $\quad v = 0.87629$ ft^3/lbm

(e) Since quality is given, this is a mixture. From Appendix A.14.

$p = 67.078$ psia $\quad h_f = 269.64$ Btu/lbm

$v_f = 0.017453$ ft^3/lbm $\quad h_{fg} = 910.64$ Btu/lbm

$v_g = 6.4627$ ft^3/lbm

$v = v_f + x(v_g - v_f) = 0.017453$ ft^3/lbm + (0.9)(6.4627 ft^3/lbm - 0.017453 ft^3/lbm)

= 5.818 ft^3/lbm

$$h = h_f + x\,h_{fg} = 269.64\ \text{Btu/lbm} + (0.9)(910.64\ \text{Btu/lbm})$$

$$= 1089.2\ \text{Btu/lb}$$

(f) Since temperature is below saturation for 1000 psia, this is a subcooled liquid. Using Appendix A.17.

$$v = 0.01658\ \text{ft}^3/\text{lbm} \qquad h = 170.32\ \text{Btu/lbm}$$

	psia	°F	v ft³/lbm	h Btu/lbm	x%	State
(a)	500	467.02	0.65	974.1	69.4	mixture
(b)	29.864	250	11.41	1000	82.6	mixture
(c)	600	700	1.0732	1351.4	100	superheated vapor
(d)	800	800	0.87624	1399.1	100	superheated vapor
(e)	67.078	300	5.818	1089.2	90	mixture
(f)	1000	200	0.01658	170.32	0	subcooled liquid

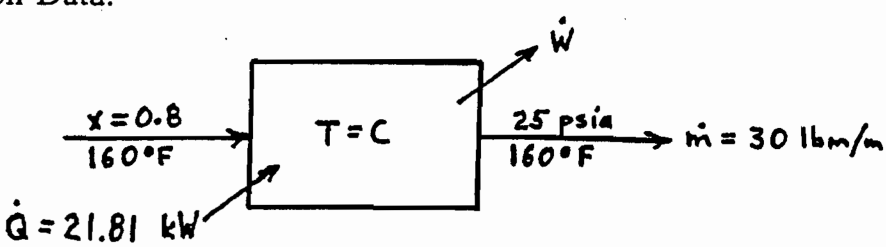
Problem *4.8

Refrigerant 12 is expanded steadily in an isothermal process. The flow rate is 30 lbm/min with an inlet state of wet saturated vapor with an 80% quality to a final state of 160°F and 25 psia. The change of kinetic energy across the device is 1.5 Btu/lbm and the heat added is 21.81 kW. Determine the system power.

Given: R 12 being expanded isothermally with heat addition and change in kinetic energy.

Find: Power.

Sketch & Given Data:



Assumptions:
1) R 12 is in equilibrium.
2) Change in potential energy is negligible.

Analysis: Using Appendix A.20 to find initial enthalpy.

h_f = 46.633 Btu/lbm $\qquad$ h_{fg} = 44.373 Btu/lbm

$$h_1 = h_f + x\,h_{fg} = 46.633 \text{ Btu/lbm} + (0.8)(44.373 \text{ Btu/lbm})$$

$$= 82.131 \text{ Btu/lbm}$$

Using Appendix A.21 to find exit enthalpy.

$$h_2 = 101.234 \text{ Btu/lbm}$$

Writing first law equation for the open system.

$$\dot{Q} + \dot{m}h_1 + \dot{m}\,ke_1 = \dot{W} + \dot{m}h_2 + \dot{m}\,ke_2$$

$$\dot{W} = \dot{Q} + \dot{m}(h_1 - h_2) + \dot{m}(ke_1 - ke_2)$$

$$= (21.81\text{kw})(56.87\text{Btu/kw-min})$$

$$+ (30\text{lbm/m})(82.131\text{Btu/lbm} - 101.234\text{Btu/lbm})$$

$$+ (30\text{lbm/m})(-1.5\text{Btu/lbm})$$

$$= 622.2\text{Btu/m}$$

(a) Writing the first law equation for the closed system.

$$Q = \Delta U + W$$

$$(3\ \text{lbm})(-212.7\ \text{Btu/lbm}) = 38.4\ \text{Btu} + W$$

$$W = -676.5\ \text{Btu}$$

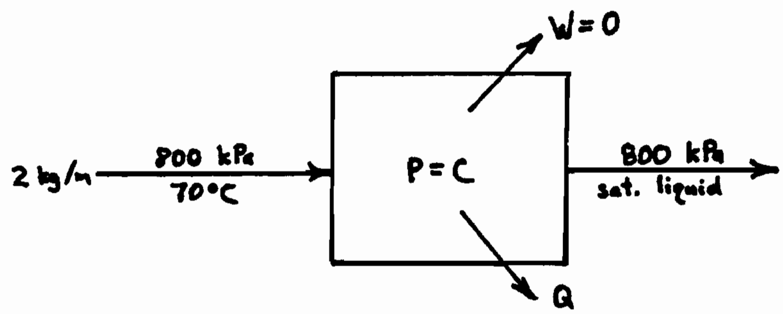
Problem 4.16

Two kilograms per minute of ammonia at 800 kPa and 70°C are condensed at constant pressure to a saturated liquid. There is no change in kinetic or potential energy across the device. Determine (a) the heat; (b) the work; (c) the change in volume; (d) the change in internal energy.

Given: Ammonia is condensed at constant pressure to a saturated liquid.

Find: The heat, work, change in volume and change in internal energy.

Sketch & Given Data:



Assumption: 1) Ammonia is in equilibrium.

Analysis: From Appendix A.10 for 800 kPa and 70°C.

$$v_1 = 0.1991 \text{ m}^3/\text{kg} \quad h_1 = 1598.6 \text{ kJ/kg}$$

$$u_1 = h_1 - P_1 v_1 = 1598.6 \text{ kJ/kg} - (800 \text{ kPa})(0.1991 \text{ m}^3/\text{kg}) = 1439.3 \text{ kJ/kg}$$

From Appendix A.9, interpolating to 800 kPa.

$$v_2 = v_f = 0.001630 \quad h_2 = h_f = 264.7 \text{ kJ/kg}$$

$$u_2 = h_2 - P_2 v_2 = 264.7 \text{ kJ/kg} - (800 \text{ kPa})(0.001630 \text{ m}^3/\text{kg}) = 263.4 \text{ kJ/kg}$$

(a) First law for open system. $\dot{W} = 0$.

$$\dot{Q} + \dot{m}h_1 = \dot{m}h_2$$

$$\dot{Q} = \dot{m}(h_2 - h_1) = \frac{(2\text{kg/min})(264.7\text{kJ/kg} - 1598.6\text{kJ/kg})}{(60\text{sec/min})}$$

$$= -44.5 \text{ kW (heat removed)}$$

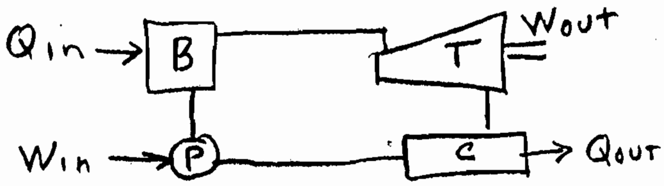
(b) $\dot{W} = 0$

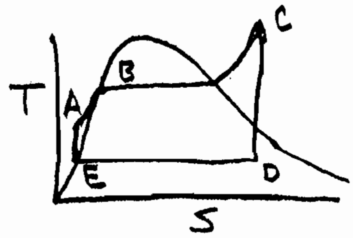
(c) $$\Delta\dot{V} = \dot{m}(v_2 - v_1) = (2\ \text{kg/min})(0.001630\text{m}^3/\text{kg} - 0.1991\text{m}^3/\text{kg})$$
$$= -0.395\text{m}^3/\text{min}$$
$$= -0.00658\text{m}^3/\text{s}$$

(d) $$\Delta\dot{U} = \dot{m}(u_2 - u_1) = \frac{(2\ \text{kg/min})(263.4\text{kJ/kg} - 1439.3\text{kJ/kg})}{(60\ \text{sec/min})}$$
$$= -39.2\ \text{kW}$$

Vapor Power Cycle

Rankine Cycle w/Superheat





Usually given P_C, T_C and P_{DE}

Solve by finding h_A, h_C, h_D, h_E

$h_E = h_f$ @ P_{DE}

$h_A = h_E + v_E(P_A - P_E)$ $\quad P_A = P_B = P_C$

h_C = superheat @ P_C, T_C, also get s_C

$s_D = s_C$ @ P_{DE}, use saturation tables

@ P_{DE}, $x = \dfrac{s_D - s_f}{s_{fg}}$ and

$h_D = h_f + x\,h_{fg}$ @ P_{DE}

Now we can solve for various values

$Q_{IN} = h_C - h_A$

$Q_{OUT} = h_E - h_D$ (negative)

$W_{OUT} = h_C - h_D$

$W_{IN} = h_E - h_A$ (negative)

$W_{NET} = h_C - h_D + h_E - h_A$

$$\eta_{TH} = \frac{W_{NET}}{Q_{IN}} = \frac{h_C - h_D + h_E - h_A}{h_C - h_A}$$

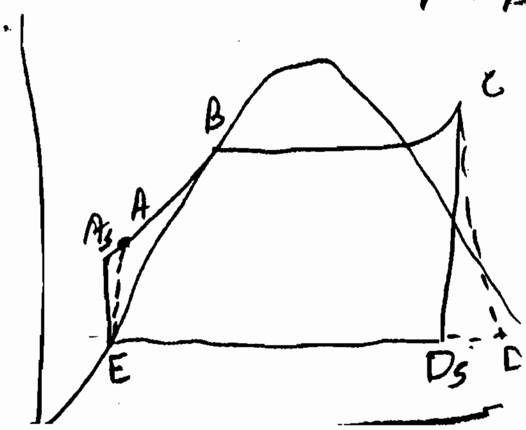
For non isentropic expansion in turbine + pump

$h_D = h_C - \eta_{ST}(h_C - h_{DS})$

$h_A = h_E + \dfrac{h_{AS} - h_E}{\eta_{SP}}$

where h_{AS} and h_{DS} would be values calculated above

η_{ST} and η_{SP} are isentropic



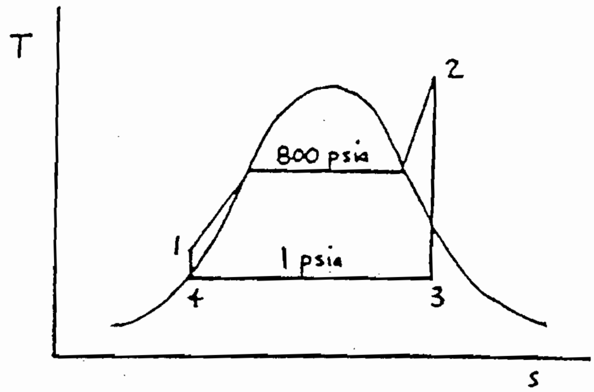
Problem *15.1

In a Rankine cycle, steam enters the turbine at 800 psia and 800°F, which exhausts at 1 psia. Show the cycle on a T-s diagram and find (a) the quality of the steam entering the condenser; (b) the turbine work in Btu/lbm; (c) the pump work in Btu/lbm; (d) the heat supplied in Btu/lbm; (e) the heat rejected in Btu/lbm; (f) the net work of the cycle in Btu/lbm; (g) the thermal efficiency of the cycle.

Given: Rankine cycle with steam expanding from 800 psia and 800°F to 1 psia.

Find: Quality of steam entering condenser, turbine work, pump work, heat rejected, net work, and thermal efficiency.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The turbine expansion and pump compression are isentropic.

Analysis: Determine the cycle enthalpies using Appendices A.14, A.15, and A.16, or SATSTM.TK and SHTSTM.TK.

h_2 = 1399.1 Btu/lbm $\qquad$ s_2 = 1.5972 Btu/lbm-R

h_3 = 892.1 Btu/lbm $\qquad$ $s_3 = s_2$ $\qquad$ (a) $\quad x = 0.794$

h_4 = 69.58 Btu/lbm $\qquad$ h_f at 1 psia

h_1 = 71.97 Btu/lbm

The turbine work is.

(b) $\quad w_t = h_2 - h_3 = 1399.1 - 892.1$ Btu/lbm $= 507$ Btu/lbm

The pump work is.

(c) $w_p = h_1 - h_4 = 71.97 - 69.58 \text{ Btu/lbm} = 2.39 \text{ Btu/lbm}$

The heat supplied is.

(d) $q_{in} = h_2 - h_1 = 1399.1 - 71.97 \text{ Btu/lbm} = 1327.1 \text{ Btu/lbm}$

The heat rejected is.

(e) $q_{out} = h_3 - h_4 = 892.1 - 69.58 \text{ Btu/lbm} = 822.5 \text{ Btu/lbm}$

The net work is.

(f) $w_{net} = w_t - w_p = 507 - 2.39 \text{ Btu/lbm} = 504.6 \text{ Btu/lbm}$

The thermal efficiency is.

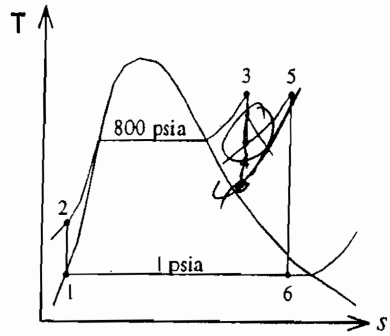
(g) $$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{504.6 \text{ Btu/lbm}}{1327.1 \text{ Btu/lbm}} = 0.380$$

9-31E A steam power plant that operates on the ideal reheat Rankine cycle is considered. The pressure at which reheating takes place, the net power output, the thermal efficiency, and the minimum mass flow rate of the cooling water required are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (*a*) From the steam tables (Tables A-4E, A-5E, and A-6E),

Given:
$P_1 = P_6 = 1$ psia
$P_2 = P_3 = 800$ psia
$T_3 = 900$ °F
$T_5 = 800$ °F
Point of Reheat is saturated vapor.



$$h_1 = h_{sat@\ 1\ psia} = 69.74 \text{ Btu/lbm}$$

$$v_1 = v_{sat@\ 1\ psia} = 0.016136 \text{ ft}^3\text{/lbm}$$

$$T_1 = T_{sat@\ 1\ psia} = 101.70°\text{F}$$

$$\begin{aligned} w_{p,in} &= v_1(P_2 - P_1) \\ &= (0.016136 \text{ ft}^3\text{/lbm})(800 - 1 \text{ psia})\left(\frac{1 \text{ Btu}}{5.4039 \text{ psia}\cdot\text{ft}^3}\right) \\ &= 2.39 \text{ Btu/lbm} \end{aligned}$$

$$h_2 = h_1 + w_{p,in} = 69.74 + 2.39 = 72.13 \text{ Btu/lbm}$$

$$\left.\begin{array}{l} P_3 = 800 \text{ psia} \\ T_3 = 900°\text{F} \end{array}\right\} \begin{array}{l} h_3 = 1455.6 \text{ Btu/lbm} \\ s_3 = 1.6408 \text{ Btu/lbm}\cdot\text{R} \end{array}$$

$$\left.\begin{array}{l} s_4 = s_3 \\ (\text{sat.vapor}) \end{array}\right\} \begin{array}{l} h_4 = h_{g@s_g=s_4} = 1178.9 \text{ Btu/lbm} \\ P_4 = P_{sat@s_g=s_4} = \mathbf{62.81\ psia} \quad \text{(the reheat pressure)} \end{array}$$

$$\left.\begin{array}{l} P_5 = 62.81 \text{ psia} \\ T_5 = 800°\text{F} \end{array}\right\} \begin{array}{l} h_5 = 1431.1 \text{ Btu/lbm} \\ s_5 = 1.8977 \text{ Btu/lbm}\cdot\text{R} \end{array}$$

$$\left.\begin{array}{l} P_6 = 1 \text{ psia} \\ s_6 = s_5 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{1.8977 - 0.13266}{1.8453} = 0.9565 \\ h_6 = h_f + x_6 h_{fg} = 69.74 + (0.9565)(1036) = 1060.7 \text{ Btu/lbm} \end{array}$$

(*b*) $$q_{in} = (h_3 - h_2) + (h_5 - h_4) = 1455.6 - 72.13 + 1431.1 - 1178.9 = 1635.7 \text{ Btu/lbm}$$

$$q_{out} = h_6 - h_1 = 1060.7 - 69.74 = 991.0 \text{ Btu/lbm}$$

Thus,

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{991.0 \text{ Btu/lbm}}{1635.7 \text{ Btu/lbm}} = \mathbf{39.4\%}$$

(*c*) The mass flow rate of the cooling water will be minimum when it is heated to the temperature of the steam in the condenser, which is 101.7°F,

$$\dot{Q}_{out} = \dot{Q}_{in} - \dot{W}_{net} = (1 - \eta_{th})\dot{Q}_{in} = (1 - 0.394)(6 \times 10^4 \text{ Btu/s}) = 3.636 \times 10^4 \text{ Btu/s}$$

$$\dot{m}_{cool} = \frac{\dot{Q}_{out}}{C\Delta T} = \frac{3.636 \times 10^4 \text{ Btu/s}}{(1.0 \text{ Btu/lbm}\cdot°\text{F})(101.7 - 45)°\text{F}} = \mathbf{641.3\ lbm/s}$$

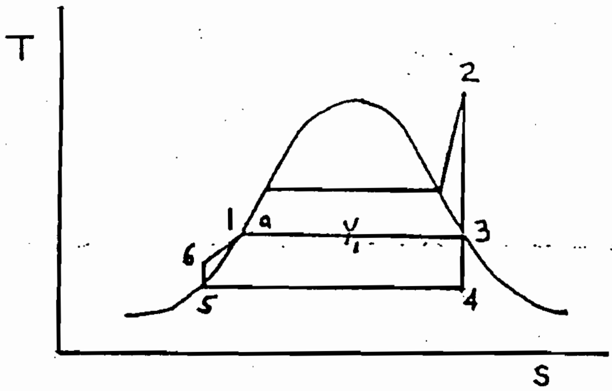
Problem *15.20

A regenerative Rankine cycle operates with one closed feedwater heater. The condensate from the heater passes through a steam trap and enters the condenser. The turbine inlet steam conditions are 1500 psia, 1100°F, and 3.6×10^5 lbm/hr. The steam expands isentropically to 100 psia, where extraction occurs for feedwater heating. The remaining steam expands to 1 psia. Determine (a) the cycle thermal efficiency; (b) the mass flow rate of steam to the feedwater heater; (c) the net power produced.

Given: Regenerative Rankine cycle with turbine inlet at 1500 psia and 1100°F, extraction at 100 psia, and exhaust at 1 psia. Inlet mass flow is 3.6×10^5 lbm/hr.

Find: Thermal efficiency, flow to feedwater heater, and net power produced.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is an ideal regenerative Rankine cycle.
4) Water leaves the heater as a saturated liquid.

Analysis: Following the procedure in example 15.5, determine the cycle enthalpies.

$h_2 = 1549.9$ Btu/lbm $\qquad s_2 = 1.639$ Btu/lbm-R

$h_3 = 1216.6$ Btu/lbm $\qquad s_3 = s_2$

$h_4 = 915.6$ Btu/lbm $\qquad s_4 = s_2$

$h_5 = 69.9$ Btu/lbm $\qquad h_f$ at 1 psia

$h_6 = 74.1$ Btu/lbm

$h_1 = h_a = 298.4$ Btu/lbm $\qquad$ (h_f at 100 psia)

Performing a first law analysis of the heater to determine y_1.

$$y_1 h_3 + h_6 = h_1 + y_1 h_4$$

$$y_1 = \frac{h_1 - h_6}{h_3 - h_4} = \frac{(298.4 - 74.1)}{(1216.6 - 298.4)} = 0.2443$$

(b) $\dot{m}_{ex} = \dot{m}_2 y_1 = (3.6 \times 10^5 \text{ lbm/hr})(0.2443) = 8.795 \times 10^4 \text{ lbm/hr}$

The net power produced is.

$$w_{net} = w_t - w_p = (h_2 - h_3) + (1 - y_1)(h_3 - h_4) - (h_6 - h_5)$$

$$w_{net} = 556.3 \text{ Btu/lbm}$$

(c) $\dot{W}_{net} = \dot{m}_2 w_{net} = (3.6 \times 10^5 \text{ lbm/hr})(556.3 \text{ Btu/lbm})$

$$= 2.003 \times 10^8 \text{ Btu/hr}$$

The thermal efficiency is.

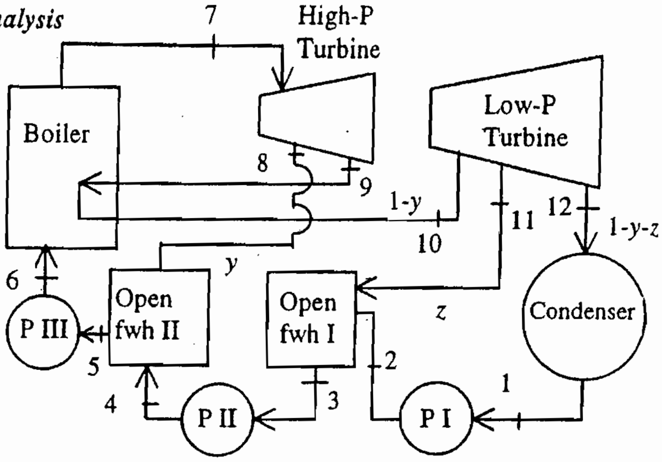
(a) $\eta_{th} = \dfrac{w_{net}}{q_{in}} = \dfrac{w_{net}}{h_2 - h_1} = \dfrac{556.3}{1549.9 - 298.4} = 0.444$

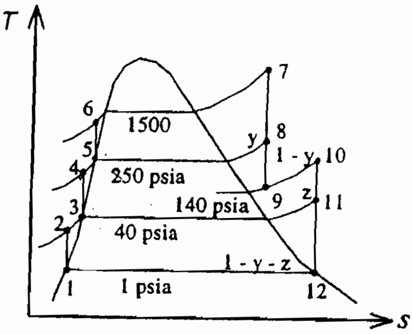
Given:
$P_6 = P_7 = 1500$ psia
$P_4 = P_5 = P_8 = 250$ psia
$P_9 = P_{10} = 140$ psia
$P_2 = P_3 = P_{11} = 40$ psia
$P_1 = P_{12} = 1$ psia
$T_7 = 1100$ °F
$T_{10} = 1000$ °F

9-45E A steam power plant operates on an ideal reheat-regenerative Rankine cycle with one reheater and two open feedwater heaters. The mass flow rate of steam through the boiler, the net power output of the plant, and the thermal efficiency of the cycle are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis





(*a*) From the steam tables (Tables A-4E, A-5E, and A-6E),

$$h_1 = h_{f\,@\,1\text{ psia}} = 69.74 \text{ Btu/lbm}$$

$$v_1 = v_{f\,@\,1\text{ psia}} = 0.016136 \text{ ft}^3\text{/lbm}$$

$$\begin{aligned} w_{pI,\text{in}} &= v_1(P_2 - P_1) \\ &= (0.016136 \text{ ft}^3\text{/lbm})(40-1 \text{ psia})\left(\frac{1 \text{ Btu}}{5.4039 \text{ psia}\cdot\text{ft}^3}\right) \\ &= 0.12 \text{ Btu/lbm} \end{aligned}$$

$$h_2 = h_1 + w_{pI,\text{in}} = 69.74 + 0.12 = 69.86 \text{ Btu/lbm}$$

$$\left.\begin{array}{l} P_3 = 40 \text{ psia} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_3 = h_{f\,@\,40\text{ psia}} = 236.16 \text{ Btu/lbm} \\ v_3 = v_{f\,@\,40\text{ psia}} = 0.017146 \text{ ft}^3\text{/lbm} \end{array}$$

$$\begin{aligned} w_{pII,\text{in}} &= v_3(P_4 - P_3) \\ &= (0.017146 \text{ ft}^3\text{/lbm})(250-40 \text{ psia})\left(\frac{1 \text{ Btu}}{5.4039 \text{ psia}\cdot\text{ft}^3}\right) \\ &= 0.67 \text{ Btu/lbm} \end{aligned}$$

$$h_4 = h_3 + w_{pII,\text{in}} = 236.16 + 0.67 = 236.83 \text{ Btu/lbm}$$

$$\left.\begin{array}{l} P_5 = 250 \text{ psia} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_5 = h_{f\,@\,250\text{ psia}} = 376.20 \text{ Btu/lbm} \\ v_5 = v_{f\,@\,250\text{ psia}} = 0.018653 \text{ ft}^3\text{/lbm} \end{array}$$

$$\begin{aligned} w_{pIII,\text{in}} &= v_5(P_6 - P_5) \\ &= (0.018653 \text{ ft}^3\text{/lbm})(1500-250 \text{ psia})\left(\frac{1 \text{ Btu}}{5.4039 \text{ psia}\cdot\text{ft}^3}\right) \\ &= 4.31 \text{ Btu/lbm} \end{aligned}$$

$$h_6 = h_5 + w_{pIII,\text{in}} = 376.20 + 4.31 = 380.51 \text{ Btu/lbm}$$

$$\left.\begin{array}{l} P_7 = 1500 \text{ psia} \\ T_7 = 1100°\text{F} \end{array}\right\} \begin{array}{l} h_7 = 1550.3 \text{ Btu/lbm} \\ s_7 = 1.6399 \text{ Btu/lbm}\cdot\text{R} \end{array}$$

$$\left.\begin{array}{l} P_8 = 250 \text{ psia} \\ s_8 = s_7 \end{array}\right\} h_8 = 1308.5 \text{ Btu/lbm}$$

$$\left.\begin{array}{l} P_9 = 140 \text{ psia} \\ s_9 = s_7 \end{array}\right\} h_9 = 1234.3 \text{ Btu/lbm}$$

$$\left.\begin{array}{l} P_{10} = 140 \text{ psia} \\ T_{10} = 1000°\text{F} \end{array}\right\} \begin{array}{l} h_{10} = 1531.0 \text{ Btu/lbm} \\ s_{10} = 1.8827 \text{ Btu/lbm}\cdot\text{R} \end{array}$$

$$\left.\begin{array}{l} P_{11} = 40 \text{ psia} \\ s_{11} = s_{10} \end{array}\right\} h_{11} = 1356.2 \text{ Btu/lbm}$$

$$\left.\begin{array}{l} P_{12} = 1 \text{ psia} \\ s_{12} = s_{10} \end{array}\right\} \begin{array}{l} x_{12} = \dfrac{s_{12} - s_f}{s_{fg}} = \dfrac{1.8827 - 0.13266}{1.8453} = 0.9484 \\ h_{12} = h_f + x_{12}h_{fg} = 69.74 + (0.9484)(1036.0) \\ \quad = 1052.3 \text{ Btu/lbm} \end{array}$$

The fraction of steam extracted is determined from the steady-flow energy balance equation applied to the feedwater heaters. Noting that $\dot{Q} \cong \dot{W} \cong \Delta ke \cong \Delta pe \cong 0$,

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\;\nearrow 0 \text{ (steady)}} = 0$$

FWH-2:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_8 h_8 + \dot{m}_4 h_4 = \dot{m}_5 h_5 \longrightarrow y h_8 + (1-y)h_4 = 1(h_5)$$

where y is the fraction of steam extracted from the turbine ($= \dot{m}_8 / \dot{m}_5$). Solving for y,

$$y = \frac{h_5 - h_4}{h_8 - h_4} = \frac{376.20 - 236.83}{1308.5 - 236.83} = 0.1300$$

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\;\nearrow 0 \text{ (steady)}} = 0$$

FWH-1

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_{11} h_{11} + \dot{m}_2 h_2 = \dot{m}_3 h_3 \longrightarrow z h_{11} + (1-y-z)h_2 = (1-y)h_3$$

where z is the fraction of steam extracted from the turbine ($= \dot{m}_9 / \dot{m}_5$) at the second stage. Solving for z,

$$z = \frac{h_3 - h_2}{h_{11} - h_2}(1-y) = \frac{236.16 - 69.86}{1356.2 - 69.86}(1 - 0.1300) = 0.1125$$

Then,

$$q_{in} = h_7 - h_6 + (1-y)(h_{10} - h_9) = 1550.3 - 380.51 + (1 - 0.1300)(1531.0 - 1234.3) = 1427.9 \text{ Btu/lbm}$$

$$q_{out} = (1-y-z)(h_{12} - h_1) = (1 - 0.1300 - 0.1125)(1052.3 - 69.74) = 744.3 \text{ Btu/lbm}$$

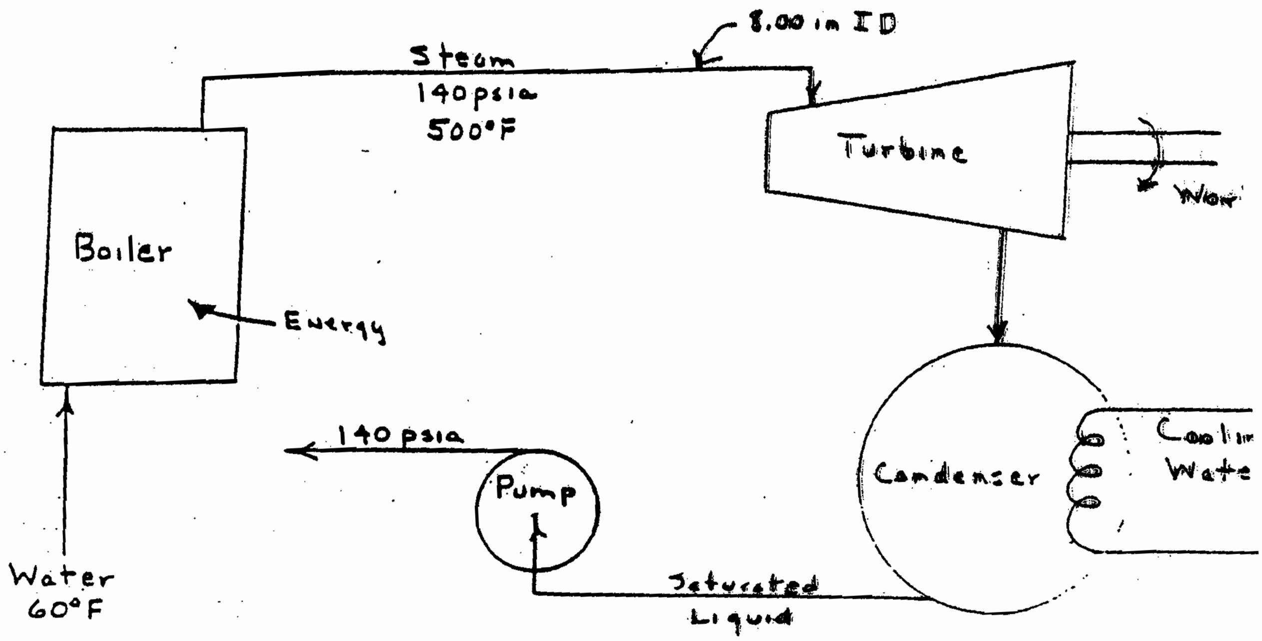
$$w_{net} = q_{in} - q_{out} = 1427.9 - 744.3 = 683.6 \text{ Btu/lbm}$$

and

$$\dot{m} = \frac{\dot{Q}_{in}}{q_{in}} = \frac{6 \times 10^5 \text{ Btu/s}}{1427.9 \text{ Btu/lbm}} = \mathbf{420.2 \text{ lbm/s}}$$

(*b*) $$\dot{W}_{net} = \dot{m} w_{net} = (420.2 \text{ lbm/s})(683.6 \text{ Btu/lbm})\left(\frac{1.055 \text{ kJ}}{1 \text{ Btu}}\right) = \mathbf{303.0 \text{ MW}}$$

(*c*) $$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{744.3 \text{ Btu/lbm}}{1427.9 \text{ Btu/lbm}} = \mathbf{47.9\%}$$



The sketch above shows a portion of a steam power plant. The rate of steam flow from the boiler to the turbine is 10,000 pounds per hour. The condenser operates at 6.00 pounds per square inch absolute and uses cooling water from a river where the temperature is 80.0°F. State regulations permit no more than a 10.0°F rise in temperature. If this condition cannot be met, the condenser is not operated.

1. The amount of energy added per pound in the boiler is most nearly

   a. 922 B.T.U.
   b. 983 B.T.U
   c. 1,247 B.T.U.
   d. 1,272 B.T.U.
   e. 1,386 B.T.U.

2. The velocity of the steam in the pipe between the boiler and the turbine is most nearly

   a. 0.0218 ft/sec
   b. 0.686 ft/sec
   c. 31.5 ft/sec
   d. 723 ft/sec
   e. 1,893 ft/sec

3. For reversible isentropic expansion through the turbine, the amount of cooling water needed is most nearly

   a. 310 ft^3/hr
   b. 970 ft^3/hr
   c. 14,380 ft^3/hr
   d. 22,450 ft^3/hr
   e. 120,300 ft^3/hr

4. The quality of the steam leaving the turbine is most nearly

a. 0.523
b. 0.634
c. 0.898
d. 0.997
e. 1.00

5. If the condenser does not operate, the steam exhausts from the turbine at atmospheric pressure. Under this condition the work output per pound for isentropic expansion in the turbine is most nearly

a. 125 B.T.U.
b. 185 B.T.U.
c. 920 B.T.U.
d. 1,095 B.T.U.
e. 1,260 B.T.U.

6. If the expansion in the turbine is not isentropic but adiabatic, which of the following statements is true?

a. The turbine efficiency will be less than in the case of isentropic expansion.
b. The rate of heat transfer from the turbine will be greater than in the case of isentropic expansion.
c. The work output of the turbine will be greater than in the case of isentropic expansion.
d. The entropy will remain constant through the turbine.
e. The temperature of the steam will remain constant throughout the expansion process.

7. Assuming an isentropic process, the pump power needed is most nearly

a. 0.023 hp.
b. 1.6 hp
c. 5.2 hp.
d. 17 hp.
e. 96 hp.

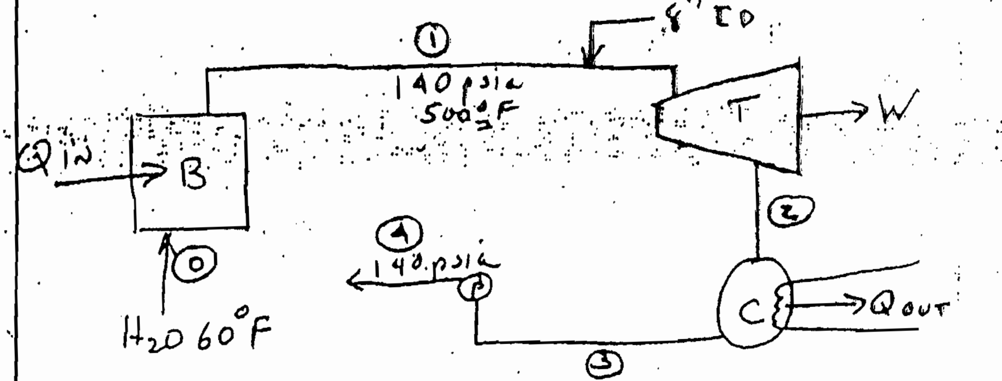
<u>Questions 8-10</u> deal with steam that is extracted at some point in the turbine for use in a certain process. This extracted steam must contain no moisture. After the steam has been used in the process it is stored in a rigid tank with a volume of 120 cubic feet.

8. If isentropic expansion is assumed in the turbine, the lowest permissible extraction pressure for the steam is most nearly

a. 25 p.s.i.
b. 45 p.s.i
c. 95 p.s.i.
d. 115 p.s.i.
e. 140 p.s.i.

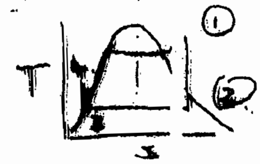
9. After the steam has been used in the process, it is stored in the rigid tank. The steam is then heated until it is saturated steam at 90.0 pounds per square inch absolute. The mass of steam in the tank is most nearly

a. 0.0408 lbm.
b. 0.256 lbm.
c. 24.5 lbm.
d. 587 lbm.
e. 6,795 lbm.



⓪ $h_0 = 28.1$

① $h_1 = 1275.2$
$s_1 = 1.6683$
$v_1 = 3.954$



1. $Q_{in} = h_1 - h_0 = 1275.2 - 28.1 = \boxed{1247.1 \text{ BTU}}$ → (C)

2. $\dot{m} = \rho A V = \frac{AV}{v}$, $V = \frac{\dot{m} v}{A} = \frac{(10{,}000/3600)(3.954)}{\pi (8)^2/4(144)} = 31.5 \frac{ft}{s}$ → (C)

3. $s_2 = s_1 = 1.6683$, at $P_2 = 6$ psia, $s_g = 1.8292$ ∴ in wet region

$X_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{1.6683 - .2472}{1.5820} = .90$

$h_2 = h_f + x h_{fg} = 137.96 + .9(996.2) = 1034.5$, $h_3 = h_f = 137.96$

$\dot{Q}_{OUT} = \dot{m}_s (h_3 - h_2) = 10{,}000\ lb/hr (137.96 - 1034.5) = -8.96 \times 10^6$ BTU/hr

$\dot{Q}_{water} = +8.96 \times 10^6$ BTU/hr $= \dot{m}_w C_{pw} (T_2 - T_1) = \dot{m}_w \left(\frac{1 \text{ BTU}}{lb\ °F}\right)(10°F)$

$\dot{m}_w = \frac{8.96 \times 10^6 \text{ BTU/hr}}{10 \text{ BTU/lb}} = .896 \times 10^6 \frac{lb}{hr} \cdot \frac{1 ft^3}{62.4 lb} = 14{,}368 \frac{ft^3}{hr}$ (C)

4. From (3) $X_2 = .90$ (C)

5. Assume Atmosphere $P_4 = 14.7$ psia, $s_2 = s_1 = 1.6683$

at 14.7 psia $s_g = 1.7566$ ∴ in wet region

$X_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{1.6683 - .3120}{1.4446} = .94$

$h_2 = h_f + x h_{fg} = 180.07 + (.94)(970.3) = 1091.7$, $h_1 = 1275.2$

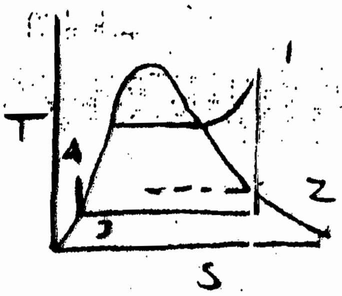
$W_T = h_1 - h_2 = 1275.2 - 1091.7 = 183.5 \frac{\text{BTU}}{lb}$ (b)

6. Turbine efficiency less (a)

7. $P_{pump} = \dot{m}_s (h_3 - h_4) = \dot{m} v_f (P_3 - P_4)$ v_f @ T_{sat} @ 6 psia $= .01645$

$P_{pump} = 10{,}000 \frac{lb}{hr} \left(.01645 \frac{ft^3}{lb}\right)(6 - 140) \frac{lbf}{in^2} \cdot \frac{144 in^2}{ft^2} \cdot \frac{HP \cdot s}{550 ft\ lbf} \cdot \frac{hr}{3600 s} =$

8. Steam $x = 100\%$ lowest pressure is when $s_{ext} = s_g = s_1 = 1.6683$



From steam tables

$s_g = 1.6669$ at 45 psia ∴ pressure is slightly above this value (b)

9. at 90 psia $v_g = 4.896\ ft^3/lb$. given $V = 120\ ft^3$

then $v = \frac{V}{m}$ and $m = \frac{V}{v} = \frac{120\ ft^3}{4.896\ ft^3/lb} = 24.5\ lbm$ (c)

Combustion

16 kg

Mass Balance / Typical - methane

$$\underline{1}\, CH_4 + \underline{2}\, O_2 = \underline{1}\, CO_2 + \underline{2}\, H_2O$$

64 kg, 44 kg, 36 kg

$$1\, CH_4 + \underline{2}\, O_2 + \underline{8.62}\, N_2 = \underline{1}\, CO_2 + 2\, H_2O + \underline{8.62}\, N_2$$ Theoretical O_2 / Theoretical Air

moles O_2 / .2319 = moles N_2

$$1\, CH_4 + \underline{2.2}\, O_2 + \underline{9.482}\, N_2 = \underline{1}\, CO_2 + \underline{2}\, H_2O + \underline{0.2}\, O_2 + \underline{9.482}\, N_2$$ / 110% Air (10% excess)

excess shows in products

$$1\, CH_4 + 2.4\, O_2 + 10.344\, N_2 = 1\, CO_2 + 2\, H_2O + \underline{0.4}\, O_2 + \underline{10.344}\, N_2$$ / 20% Excess Air, 120% Air

Excess Air usually needed to ensure complete combustion. The more air (nitrogen) the more energy taken away by air (nitrogen) leaving. Trade off - complete comb vs efficiency. Insufficient air produces CO_2 and CO (carbon monoxide)

Dry products of last equation (20% excess Air) are CO_2, O_2 and N_2, H_2O is wet

CHAPTER TWELVE

Problem 12.1

A fuel mixture of 50% C_7H_{16} and 50%C_8H_{18} is oxidized with 20% excess air. Determine (a) the mass of air required for 50 kg of fuel; (b) the volumetric analysis of products of combustion.

Given: Fuel mixture of 50%C_7H_{16} and C_8H_{18} burned with 20% excess air.

Find: Mass of air required for combustion of 50 kg fuel and volumetric analysis of products.

Assumptions:

1) The combustion is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.

Analysis: Writing the reaction for 100% theoretical air and 100 total moles of fuel.

$$50\ C_7H_{16} + 50\ C_8H_{18} + a\ 0_2 + 3.76\ a\ N_2 \rightarrow b\ CO_2 + c\ H_{20}$$

$b = 750 \qquad c = 850 \qquad a = 1175$

Writing the equation for 120% theoretical air.

$$50\ C_7H_{16} + 50\ C_8H_{18} + (1.2)(1175)O_2 + (3.76)(1.2)(1175)\ N_2 \rightarrow$$

$$750\ CO_2 + 850\ H_2O + (3.76)(1.2)(1175)\ N_2 + (.2)(1175)\ O_2$$

$$r_{a/f} = \frac{(1410+5301.6 \text{ mol air})(28.97 \text{ kg/kgmol air})}{[(50)(100)+(50)(114) \text{ kg fuel}]}$$

$= 18.2$ kg air/kg fuel

(a) (50 kg fuel)(18.2 kg air/kg fuel) = 910 kg air

(b) Total moles of product = 750 + 850 + 5301.6 + 235 = 7136.6 mol

$$CO_2 = \frac{750}{7136.6} = 0.105 \qquad H_{20} = \frac{850}{7136.6} = 0.119$$

$$N_2 = \frac{5301.6}{7136.6} = 0.743 \qquad O_2 = \frac{235}{7136.6} = 0.033$$

Problem 12.3

What mass of liquid oxygen is required to completely burn 1000 kg of liquid butane, C_4H_{10}, on a rocket ship?

Given: 1000 kg of C_4H_{10} burned completely.

Find: Mass of liquid O_2.

Assumptions: 1) The only products are CO_2 and H_20.

Analysis: Write the balanced combustion equation.

$$C_4H_{10} + 6.5\ 0_2 \rightarrow 4\ CO_2 + 5\ H_20$$

$$r_{a/f} = \frac{(6.5 \text{ mol } 0_2)(32 \text{ kg/kgmol})}{(1 \text{ mol butane})(58 \text{ kg/kgmol})} = 3.586 \text{ kg}0_2/\text{kg butane}$$

$$m_{02} = (3.586)(1000) = 3586 \text{ kg } 0_2$$

Problem 12.5

With 110% theoretical air, 1 kgmol of methane is completely oxidized. The products of combustion are cooled and completely dried at atmospheric pressure. Determine (a) the partial pressure of oxygen in the products; (b) the mass in kg of water removed.

Given: Methane oxidized with 110% theoretical air and cooled.

Find: Partial pressure of oxygen and water condensed.

Assumptions:
1) Oxidation is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.
4) Atmospheric pressure is 101.325 kPa.

Analysis: Writing the balanced reaction equation for 100% theoretical air.

$$CH_4 + a\ O_2 + 3.76a\ N_2 \rightarrow b\ CO_2 + c\ H_2O + 3.76\ aN_2$$

$b = 1 \qquad c = 2 \qquad a = 2$

Writing the equation for 110% theoretical air.

$$CH_4 + (1.1)(2)O_2 + (1.1)(3.76)(2)N_2 \rightarrow CO_2 + 2\ H_2O + 8.272\ N_2 + (.1)(2)\ O_2$$

Moles of product (without H_2O) = 1 + 8.272 + .2 = 9.472

(a) O_2: $\dfrac{0.2\text{ mol}}{9.472\text{ mol}} = 0.021 \qquad P_{O_2} = (0.021)(101.325\text{ kPa}) = 2.13\text{ kPa}$

(b) 2 moles of H_2O are condensed.

2 mol H_2O = 36 kg

Problem 12.7

Write the combustion equation for gaseous dodecane and theoretical air. Determine (a) the fuel/air ratio on the mass basis; (b) the fuel/air ratio on the mole basis; (c) the mass of fuel/mass of water formed; (d) the molecular weight of the reactants; (e) the molecular weight of the products; (f) the ratio of moles of reactants to moles of products.

Given: Dodecane being burned in theoretical air.

Find: Fuel/air ratio on a mass and mole basis; ratio of fuel to water formed, molecular weight of the reactants and products, the molal ratio of reactants to products.

Assumptions:
1) The combustion is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.

Analysis: Writing the combustion equation.

$$C_{12}H_{26} + aO_2 + 3.76\,aN_2 \rightarrow b\,CO_2 + cH_2O + 3.76\,aN_2$$

$$b = 12 \qquad c = 13 \qquad a = b+\frac{c}{2}=12+\frac{13}{2}=18.5$$

$$C_{12}H_{26} + 18.5O_2 + 69.56\,N_2 \rightarrow 12\,CO_2 + 13\,H_2O + 69.56\,N_2$$

(b) $$r_{f/a} = \frac{1\text{ mol fuel}}{18.5+69.56\text{ mol air}} = 0.01136\frac{\text{mol fuel}}{\text{mol air}}$$

(a) $$r_{f/a} = \frac{(1\text{ mol fuel})[(12)(12)+26\text{ kg/mol}]}{(18.5+69.56\text{ mol})(28.97\text{ kg/mol})}=0.0666\frac{\text{kg fuel}}{\text{kg air}}$$

(c) $$\frac{\text{mass fuel}}{\text{mass }H_2O}=\frac{(1\text{ mol})(170\text{ kg/mol})}{(13\text{ mol})(18\text{ kg/mol})}=0.726\frac{\text{kg fuel}}{\text{kg air}}$$

(d) $$M_R=\frac{\text{kg reactants}}{\text{mol reactants}}=\frac{170\text{ kg}+(18.5)(32)\text{kg}+(69.56)(28)\text{kg}}{1\text{ mol}+18.5\text{ mol}+69.56\text{ mol}}=30.4\frac{\text{kg}}{\text{kg mol}}$$

(e) $$M_P=\frac{\text{kg products}}{\text{mol products}}=\frac{(12)(44)\text{kg}+(13)(18)\text{kg}+(69.56)(28)\text{kg}}{12\text{ mol}+13\text{ mol}+69.56\text{ mol}}=28.65\frac{\text{kg}}{\text{kg mol}}$$

(f) $$\frac{n_R}{n_P}=\frac{1\text{ mol}+18.5\text{ mol}+69.56\text{ mol}}{12\text{ mol}+13\text{ mol}+69.56\text{ mol}}=0.942$$

Problem 12.8

A coal sample has the following ultimate analysis on a dry basis: 81%C, 2.5% H_2, 0.6% S, 3.0% O_2, 1.0% N_2, and 11.9% ash. Determine the reaction equation for 100% theoretical air.

Given: Coal with known ultimate analysis is burned in 100% theoretical air.

Find: Reaction equation.

Assumptions:
1) The combustion is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.

Analysis: Determine the mole fractions of the coal's constituents on an ashless basis. See example 12.3.

	x_i	M_i	x_i/M_i	y_i
C	0.9194	12	0.07662	0.8283
H_2	0.0284	2	0.01420	0.1535
S	0.0068	32	0.00021	0.0023
O_2	0.0341	32	0.00107	0.0116
N_2	0.0113	28	0.00040	0.0043
	1.0000		0.0925	1.0000

Writing the reaction equation.

$$0.8283C + 0.1535\,H_2 + 0.0023S + (0.0116+a)\,O_2$$

$$+ (0.0043+3.76a)\,N_2 \rightarrow 0.8283\,CO_2 + 0.1535\,H_2O$$

$$+ 0.0023\,SO_2 + (0.0043+3.76a)\,N_2$$

$$O_2 \text{ balance: } 0.0016+a = 0.8283+\frac{0.1535}{2}+0.0023$$

$$a = 0.9058$$

$$0.8283C + 0.1535\,H_2 + 0.0023S + 0.9174\,O_2 + 3.41\,N_2 \rightarrow$$

$$0.8283\,CO_2 + 0.1535\,H_2 + 0.0023\,SO_2 + 3.41\,N_2$$